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A high-brightness, accelerator-based EUV source for actinic mask inspection

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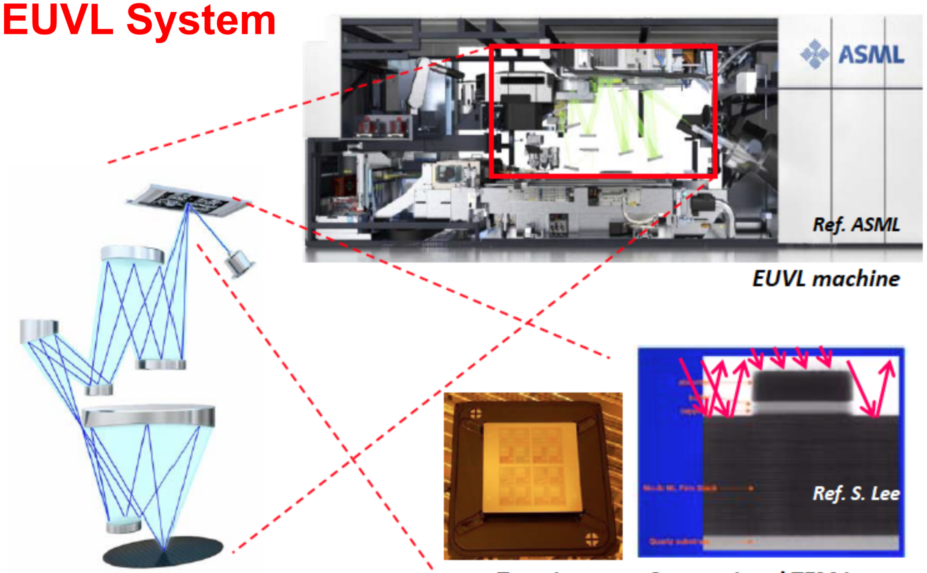
Outline

- **Background & Motivation**
  – EUV mask inspection
  – Actinic patterned mask inspection using lensless imaging
  – Source requirements
- **COSAMI: Accelerator-based high-brightness EUV source**
  – Optics design
  – Technical sub-systems
    – Undulator
    – Vacuum system
    – Injector linac
    – Radio-frequency sytem
    – Radiation shielding
- **Conclusions**

Not discussed
– *Magnets*
– *Non-critical subsystems (diagnostics, controls, power supplies)*
– *Injection to storage ring*

EUV Mask inspection

EUVL System



EUVL machine

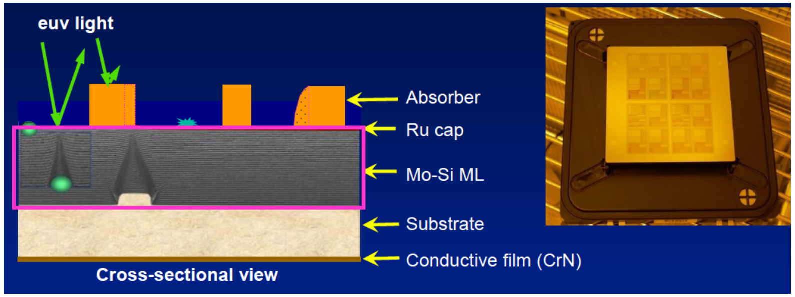
EUV optics

Top view

Crossectional TEM image EUV mask

Mask inspection:

- Masks are Mo/Si multilayer
- Mask inspection is a big challenge:
  - Mask blank inspection
  - Patterned mask inspection
  - Mask review



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Actinic mask metrology for EUVL is missing

EUV Infrastructure Readiness Snapshot

Judged as of Today

EUV infrastructure has 8 key programs

3 are ready or near-ready now, 4 are in development, 1 has significant gaps

- **E-beam Mask Inspection**: In use for low volume production. Need TPT increase.
- **Actinic Blank Inspection (ABI)**: Ready for qualification of HVM quality blanks
- **AIMS Mask Inspection**: Imaging demonstrated; systems shipping to field
- **Pellicle**: ASML commercializing – needs acceleration; production phase in 2H'17 – cannot slip schedule
- **EUV blank quality**: Process and yield improvements continue
- **Blank multi-layer deposition tool**: Improving defect results. Multiple deposition techniques being evaluated to define HVM tool approach.
- **EUV resist QC:** RMQC center at IMEC expected online in 2017
- **Actinic Patterned Mask Inspection (APMI)**: High resolution PWI for fab. Still need actinic inspection in mask shop.

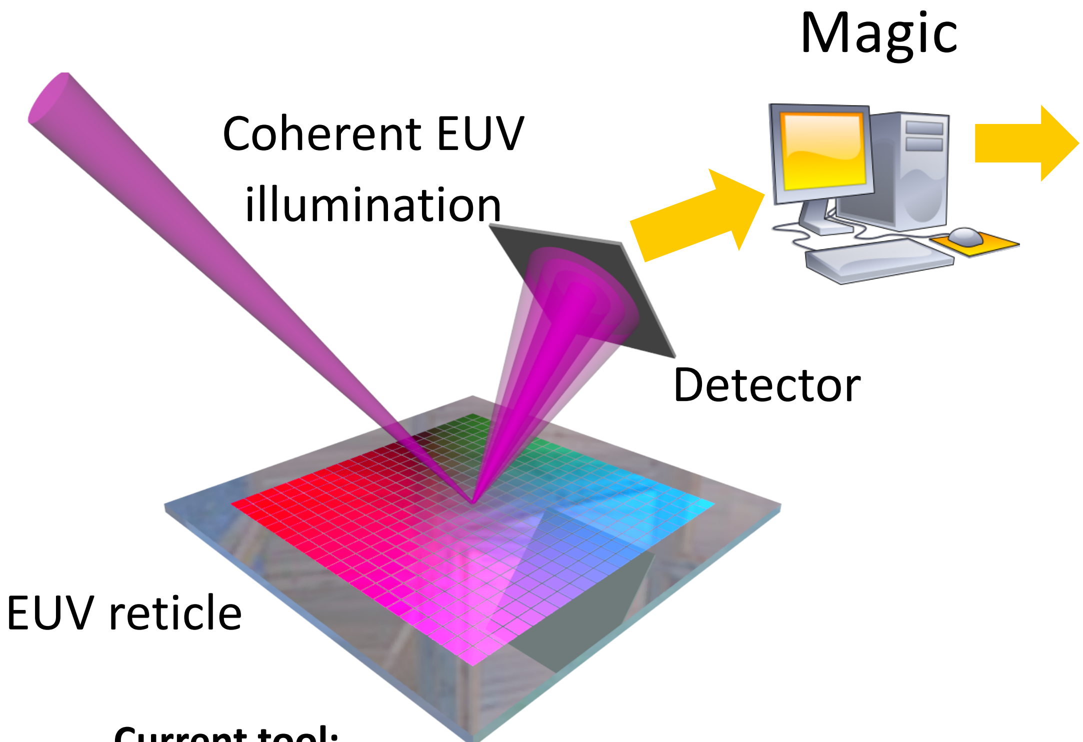
Britt Turkot/ Intel 2016 International Symposium on EUV Lithography, 24 October 2016, Hiroshima, Japan intel

SPIE BACUS MEETING, Monterey, September 2017

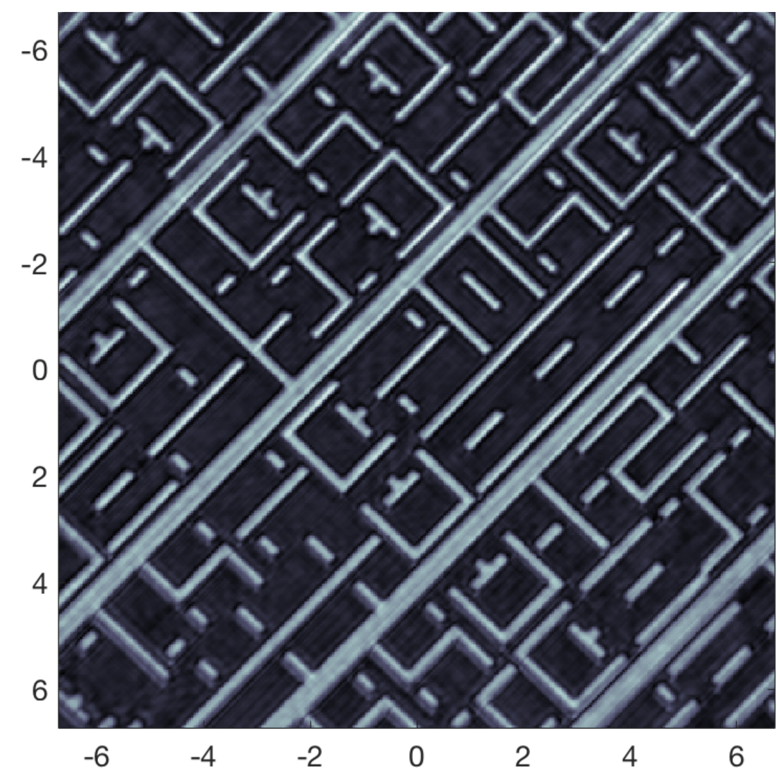
Panel Discussion: How to survive the first and even second node of EUV without actinic mask inspection?

EUV Source is the major challenge: Limited brighnetness (not flux) and stability and availability

Actinic pattern inspection platform based on Coherent Diffraction Imaging (CDI)



Reconstructed aerial image



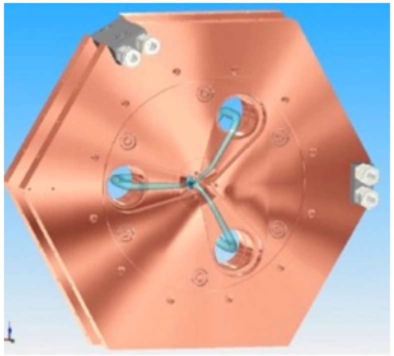
Current tool:

- Synchrotron-based
- $\lambda/\Delta\lambda \approx 1500$
- Max sample size: 2×2 cm^2
- Inspection area: 200x200 µm^2
- Na_{max}: 0.24
- Resolution limit: 34 nm

This method requires much higher brightness than other imaging or inspection methods!!

EUV source for metrology

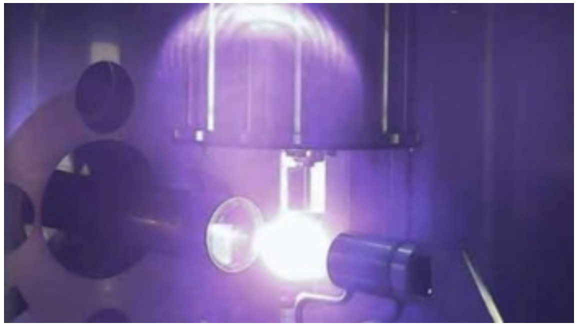
Z-pinch



- Off-the-shelf
- High availability
- Maintenance
- Debris
- Sufficient flux
- Low-brightness

10 W/mm^2.sr

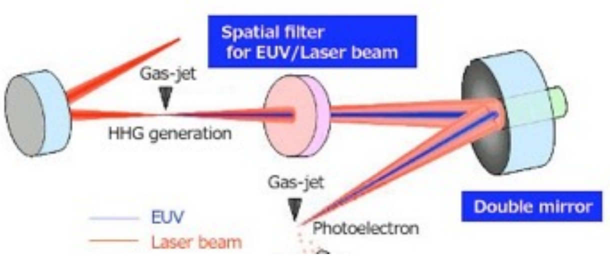
LPP/DPP



- Low availability
- Low stability
- Debris
- Maintenance
- High flux
- Relatively high brightness

100 W/mm^2.sr

HHG

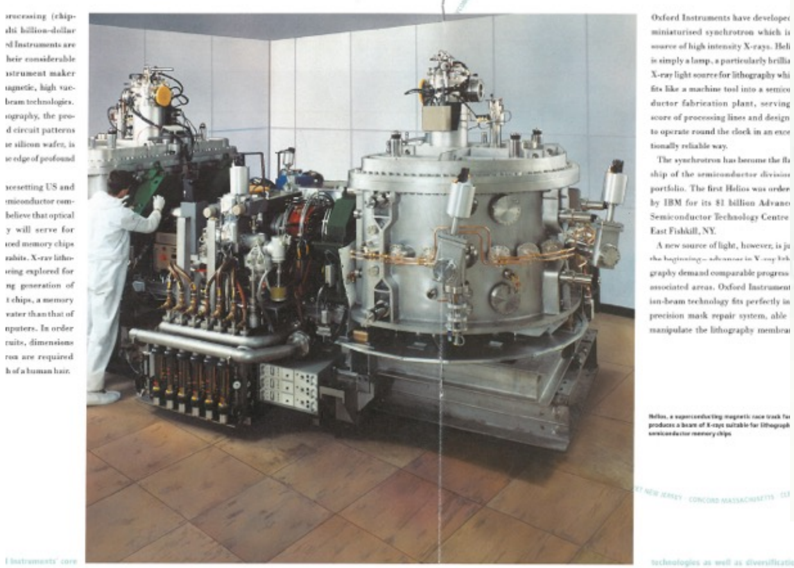


- Low availability
- Low stability
- High brightness
- Low flux

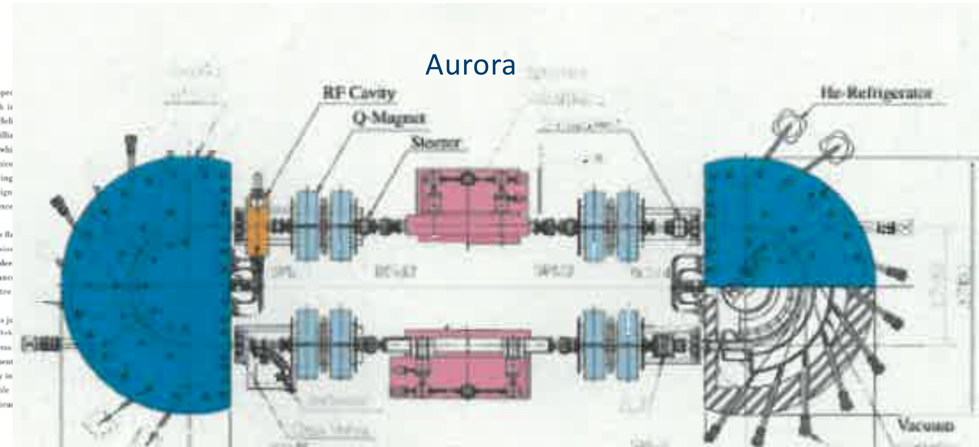
1 μW

Compact sources

Helios



Aurora



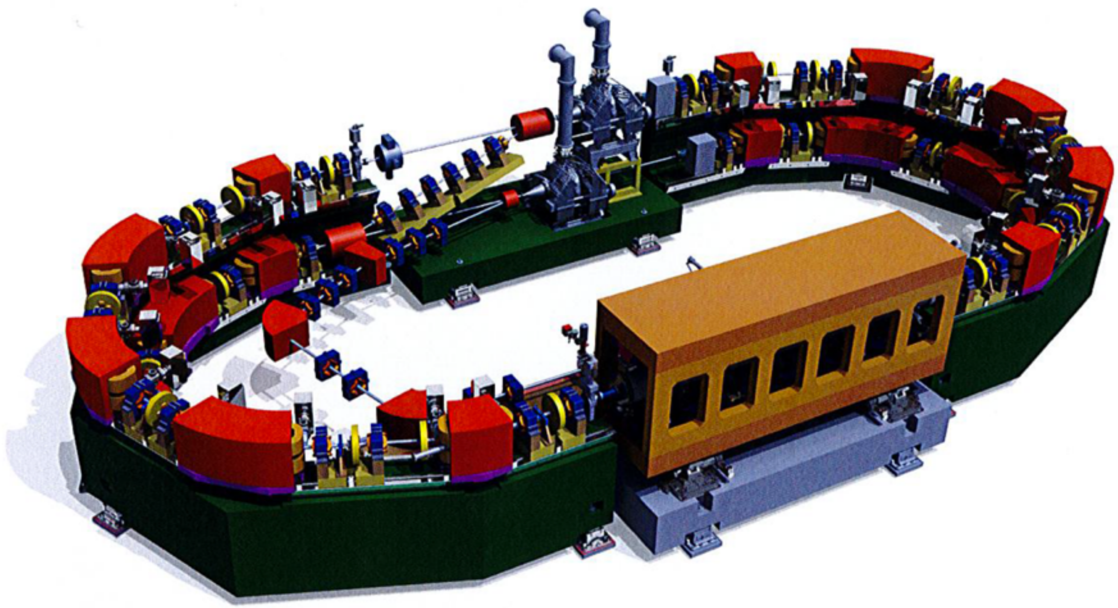
Well established technology:

- Many tools are developed in 80s and 90s
- Designed for HVM but could not achieve the moving target of power requirements

Motivation for this study

- A source for EUV metrology:
  - Sufficient Flux to perform mask inspection within 7 hours, i.e. 100 mW
  - High coherence for CDI
  - Intensity stability (0.1%)
  - Compactness:
    - As compact as possible
    - But without increasing the machine complexity
    - Really compact
  - Minimal down time: Scheduled (<5%) and unscheduled (<1%)
  - Reliability: use proven technology and rebust design
  - Cost& Development Time

Compact EUV Metrology Source „COSAMI“



Wavelength	13.5 nm
Flux	~100 mW
Brilliance	~ 10^9 W/(mm^2 · strd)
Beam energy/beam current	430 MeV/150 mA
Pulse structure	~50 ps every 2 ns
Injection system	Top-up mode
Beam stability	0.1%
Availability	>95%
Reliability	<1% down time
Footprint	5m × 12m

Innovative solutions

→ adapt technology of Diffraction Limited Storage Rings

→Co-centric design: vertical stacking of booster and ring → small footprint

→ multi-bend magnet lattice

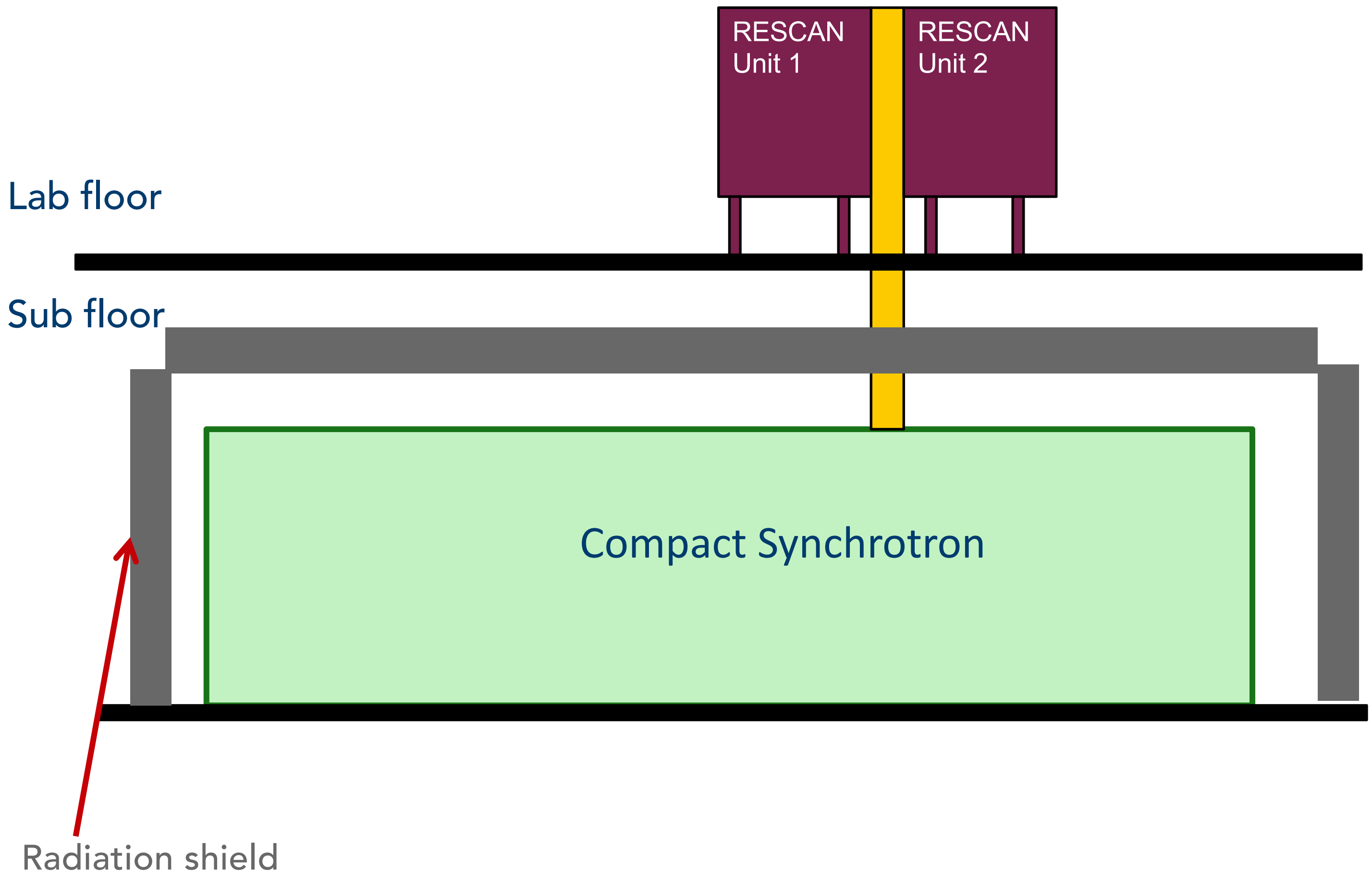
→ implementation of undulator

→ combined function magnets

→ small vacuum chambers with NEG coating

→Photo injector

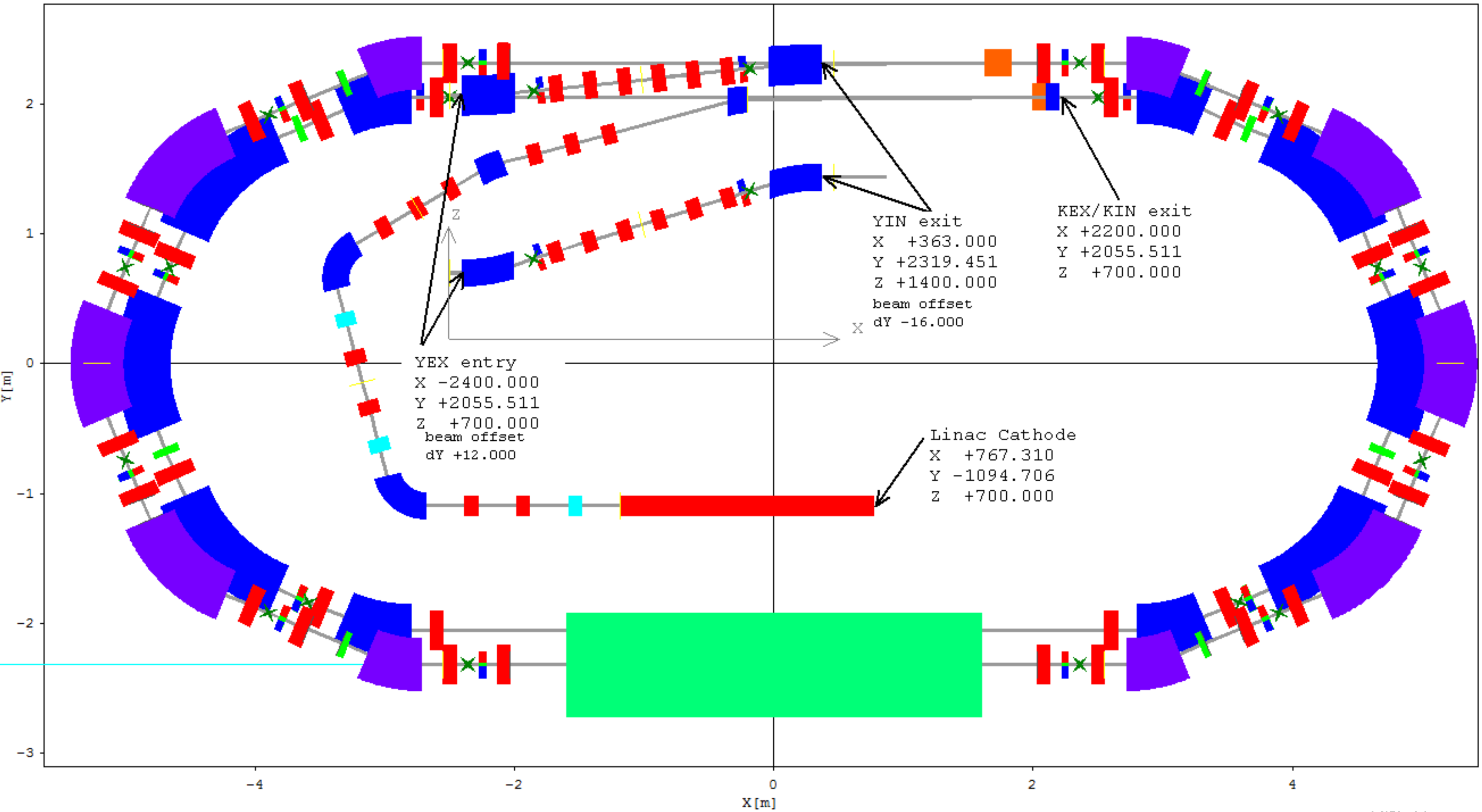
Does it fit into a fab?



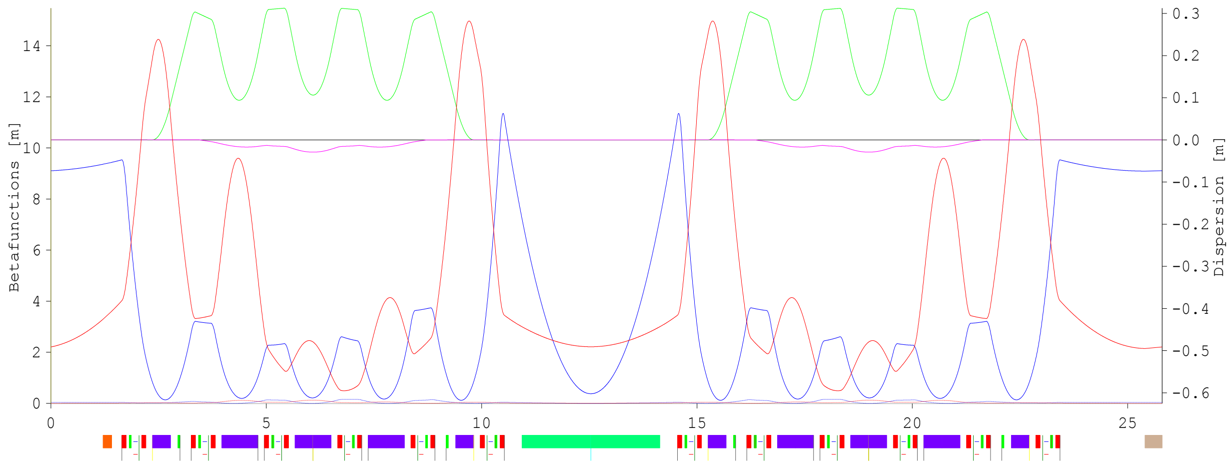
Facility layout

Race-track geometry: Two 5-bend achromat arcs and two straights. One straight for the undulator and one for injection and RF.

- Ring: 430 MeV, 25.8 m
- Booster: 43 → 430 MeV, 24.0 m
- BR transfer line -18.6° inclination
- LB transfer line
- Gun/Linac: 43 MeV, 2.1 m



Linear optics design



Storage ring optical functions (β_x , β_y , D_x, D_y)

Lattice design

- Strong horizontal focussing: strong quads → small magnet bore; strong sextupoles to correct chromaticity.
- Weak dispersion (MBA) ensures adequate momentum acceptance despite small aperture → needed to reduce particle loss to Touscheck scattering.
- Skew-quad windings in sextupole to generate some vertical emittance → reduce Touscheck scattering.
- Small β_x at center of undulator → minimise source-point size → brightness.
- β_y reduced at undulator extremities to reduce particle losses (small vertical gap).
- Magnetic elements would be installed / aligned on girders. Simulations show orbit correction due to misalignments (100 µm, 100 µrad) easily corrected with 1 mrad correction coils.

Nominal storage ring parameters

Circumference [m]	25.8	Energy [MeV]	430
Working Point $Q_{x/y}$	4.73 / 1.58	Radiation loss/turn [keV]	2.83
Natural chromaticity $\xi_{x/y}$	-9.7 / -6.9	Emittance [nm]	5.50
Momentum compaction α_c	0.0258	Relative energy spread	$4.13 \cdot 10^{-4}$
Hor. damping partition J_x	1.54	Damping times $\tau_{x/y/E}$ [ms]	16.6 / 25.6 / 17.5

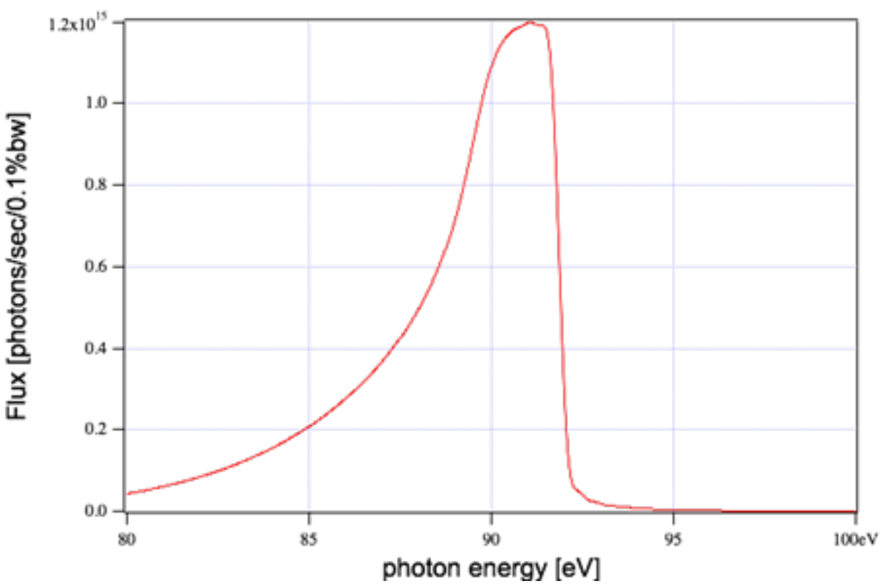
Machine length corresponds to 43 RF wavelengths. 24 "buckets" are filled to leave a gap in the bunch train to combat trapped ions. Total charge in ring is ~ 17 nC (assuming I = 200 mA, to have some margin).

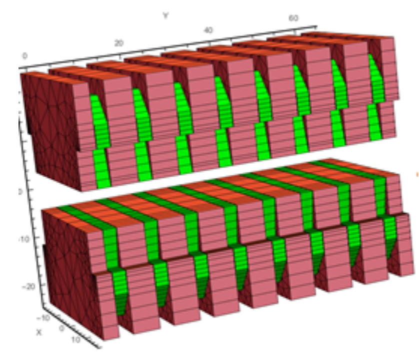
Non-linear beam dynamics studies investigated to evaluate:
Dynamic aperture ✓ greater than physical aperture
Touscheck scattering → 400 kV RF voltage needed to optimise life-time
Intra-beam scattering → some emittance dilution.

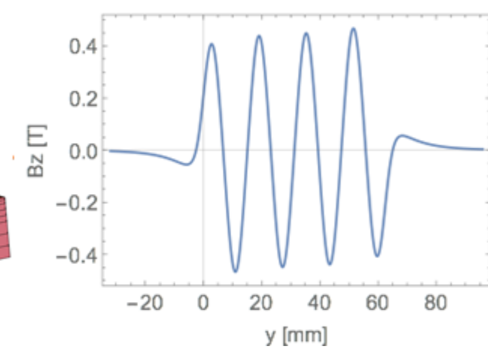
Life-times of ~ 15 minutes calculated → Top-up frequency > 1 Hz to maintain 0.1% intensity stability.

The Undulator

- Design based on undulator assemblies for SLS and SwissFEL.
  - Field on axis = 0.42 T, λ_u = 16 mm, gap = 7 mm (fixed in operation).
  - Good field region = ± 12 mm
  - Magnetic material: NdFeB with diffused Dy → good combination of B_r and H_c → less sensitive to demagnetisation due to beam loss (i.e. radiation hard).
- Produces flux / brightness required for mask inspection at 13.5 nm (92 eV).
  - Flux = 1.2×10^{15} ph/s/0.1% BW
  - Brilliance = 6×10^{17} ph/s/mm^2/mrad^2/0.1% BW

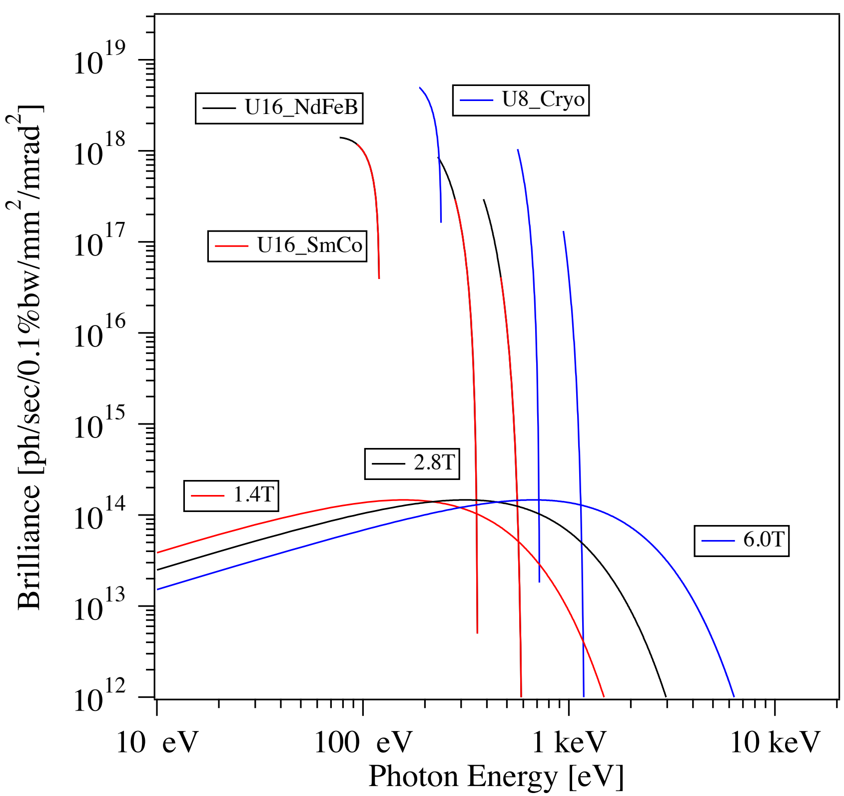


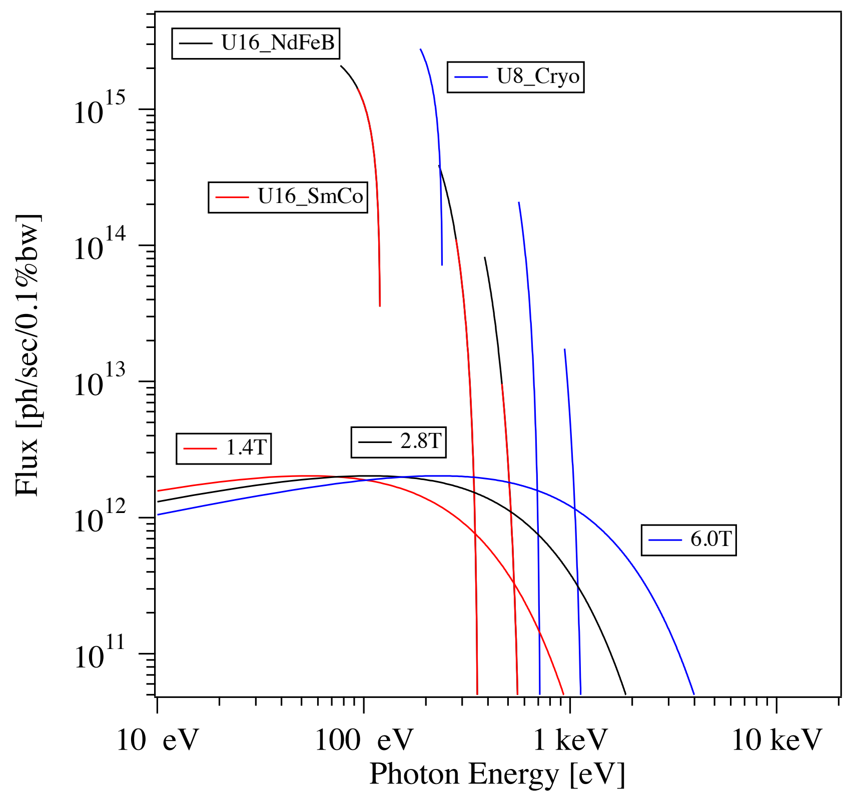




Simulation of 4 periods

EUV source brightness curves – 430 MeV comparison with other undulator / dipole magnets

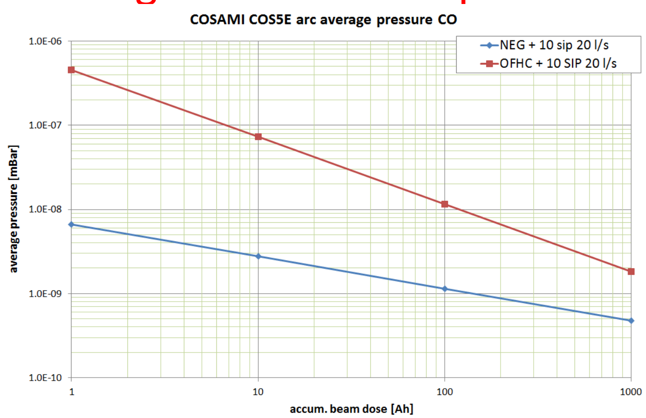


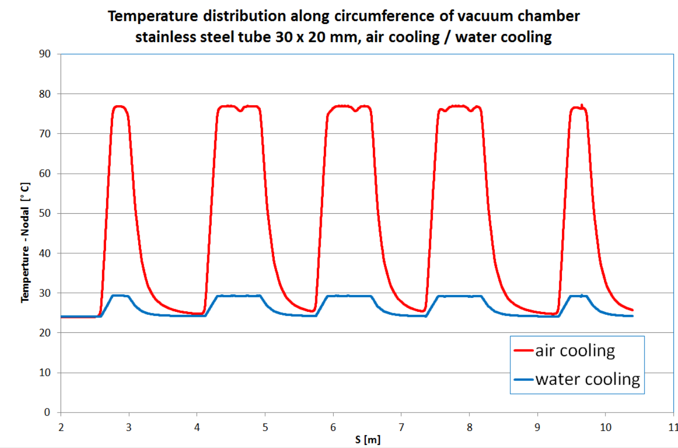


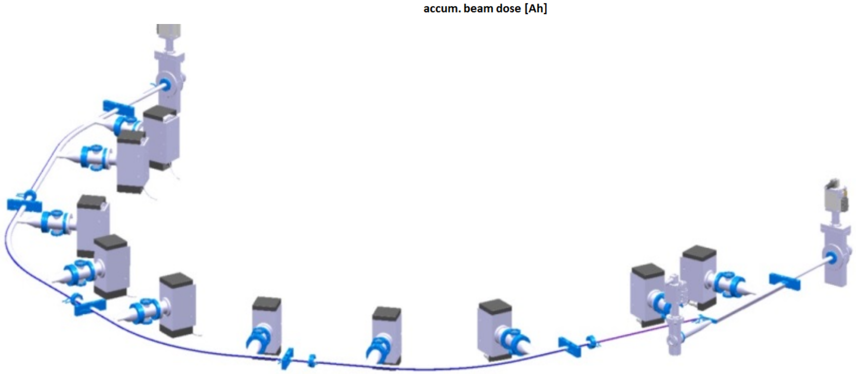
Vacuum system

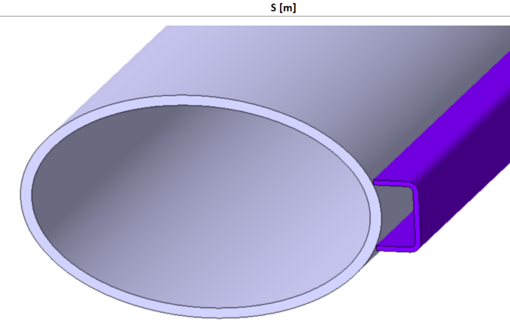
- Vacuum system must provide sufficiently low base pressure (< 10^{-9} mbar) to due to scattering from residual gas.
  - Elliptical vacuum chamber of 30 mm (H) x 20 mm (V) adopted.
  - “small” chamber to allow strong magnet gradients.
- Base pressure dominated by photo-desorption   due to synchrotron radiation.
- Low energy ring → low heat load ~ 85 W/m but temperature rise is still significant
  - Forced cooling needed

→ full NEG coating of chamber required



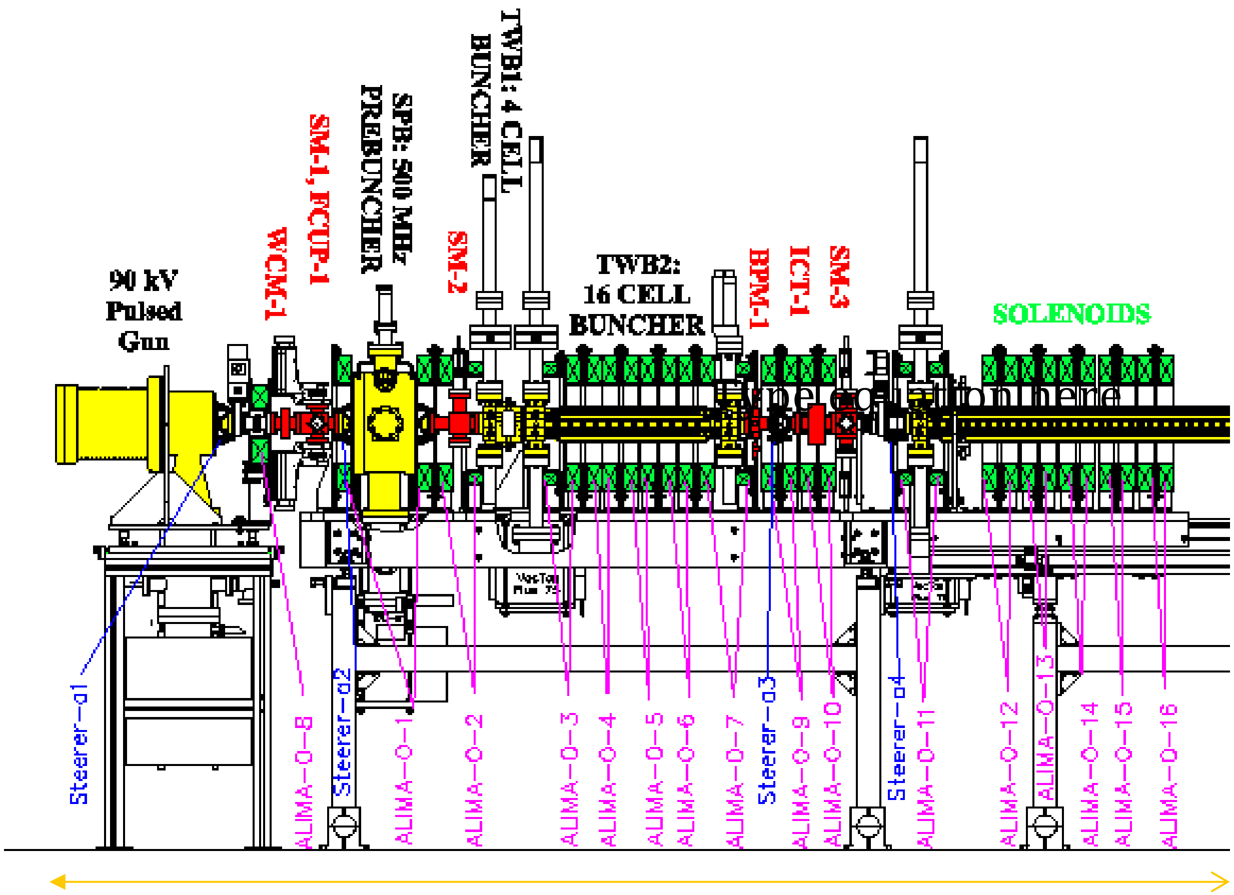






Cooling channel 3mm x 6mm

Standard Injector Linac: available commercially

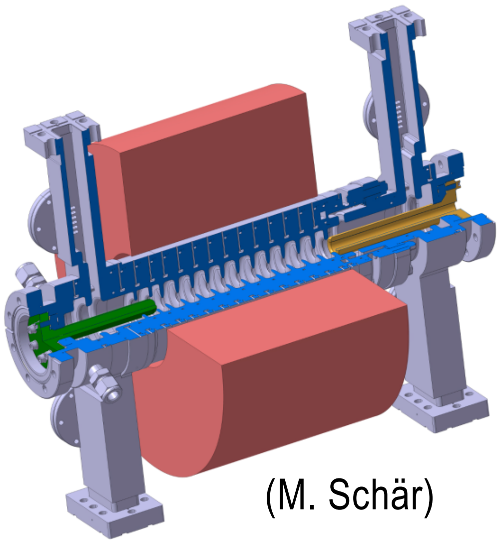


Ca. 4m for bunching and acceleration to 20MeV

- Proven technology
- Can be fed by 1 S-band Klystron
- Needs space for HV-area and bunching!
- Needs complex waveguide system
- Some jitter in energy and charge
- Needs about 5x5m2 floor space for Klystron and magnet power supplies

Takes up too much space !

The EUV source would use a Photo-Injector linac



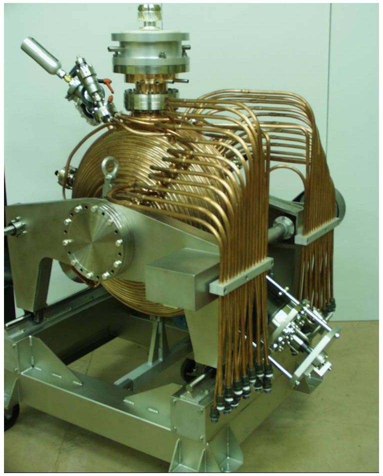
(M. Schär)

- Combine the high brighness **travelling wave gun** with **SwissFEL 2m C-band structure**:
  Relaxed gradient, laser profile and repetition rate,
  Increas number of cells to reach the energy,
  simplify the couplers and focusing magnet.

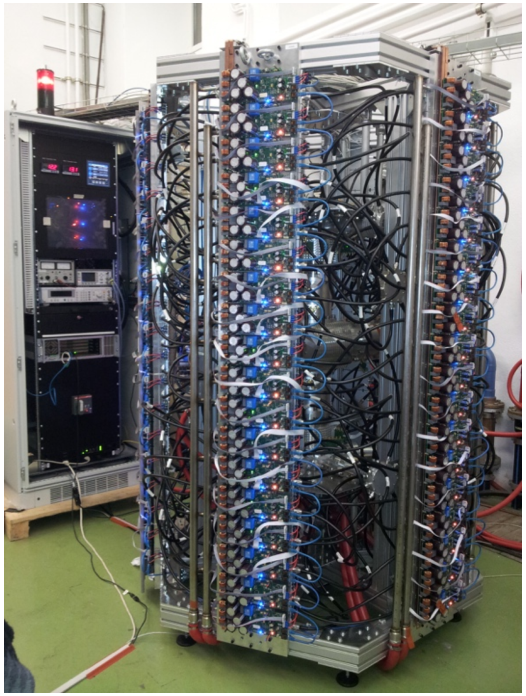
- Advantages: Compact and simple design
- Needs UV-Laser system
- Synchronization more complex !
  With f_b=71.4MHz: 5.712GHz = $80f_b$
  499.8MHz = $7f_b$
- Timing for bucket allocation in storage ring more complex (but can still be achieved).

SR Radio-Frequency system

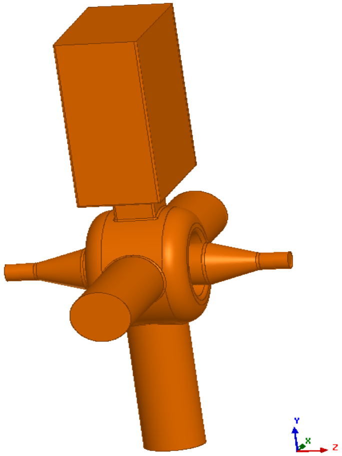
Identification of hardware requirements – use existing commercial solutions



ELETTRA 500 MHz cavity



65 kW solid state amp.



ALS 3rd harmonic cavity

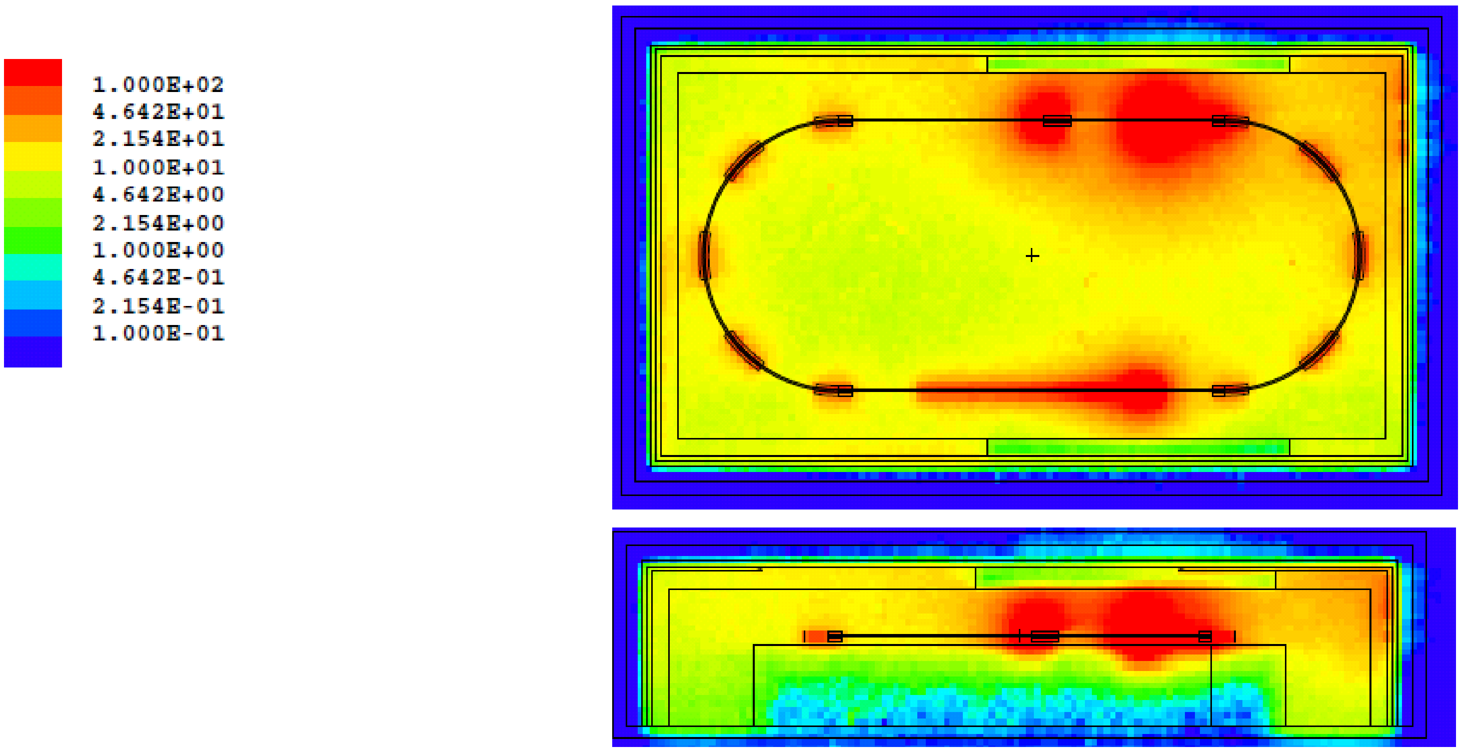
RF cavity, power source, waveguide, phase/amplitude regulation

Studies of instability thresholds → shows advantage of 3rd Harmonic Cavity (3HC)

Microwave instability driven by ring impedance; CBI driven by longitudinal or transverse Higher Order Modes of the RF cavity.

Radiation shielding

- Performed using codes MCNPX 2.7.0 (local) / MCNP 6.1 (outer wall)
  Loss rates ~ 1.2×10^8 electrons/s at 430 MeV → ICRP data used to convert flux to dose rates. Losses dominated by storage ring.



Ensuring the radiation safety is straightforward.

Summary

- COSAMI is a viable solution to the EUV metrology in general
- We did conceptual design and studie the sub-systems

- Optimization undulator vs. storage ring

→Conceptual design
- – Lattice design
  - – layout & performance ✓
  - – non-linear dynamics ✓
  - – beam lifetime ✓
  - – ion trapping ✓
  - – injection to storage ring **(WIP)**
- – Undulator ✓
- – DC-Magnets ✓
- – Pulsed magnets **(WIP)**
- – RF-systems ✓
- – Vacuum system ✓
- – Radiation shielding ✓ Local shielding **(WIP)**
- – Non-critical subsystems: diagnostics, controls, power supplies

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Thanks for your attention.